Heavy flavor and the energy loss

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Jet suppression
– a traditional probe of QCD matter

Light and heavy flavour suppressions have been considered as excellent probes of QCD matter.

↓

Suppression for a number of observables at RHIC and LHC has been measured.

↓

Comparison of theory with the experiments allows testing our understanding of QCD matter.

Some problems as well

However, results of some measurements appear strongly counterintuitive.

↓

Example: **Heavy flavor puzzle at RHIC, which led some theorists to seek explanation outside of perturbative QCD.**

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Similar puzzling data appear at LHC as well.

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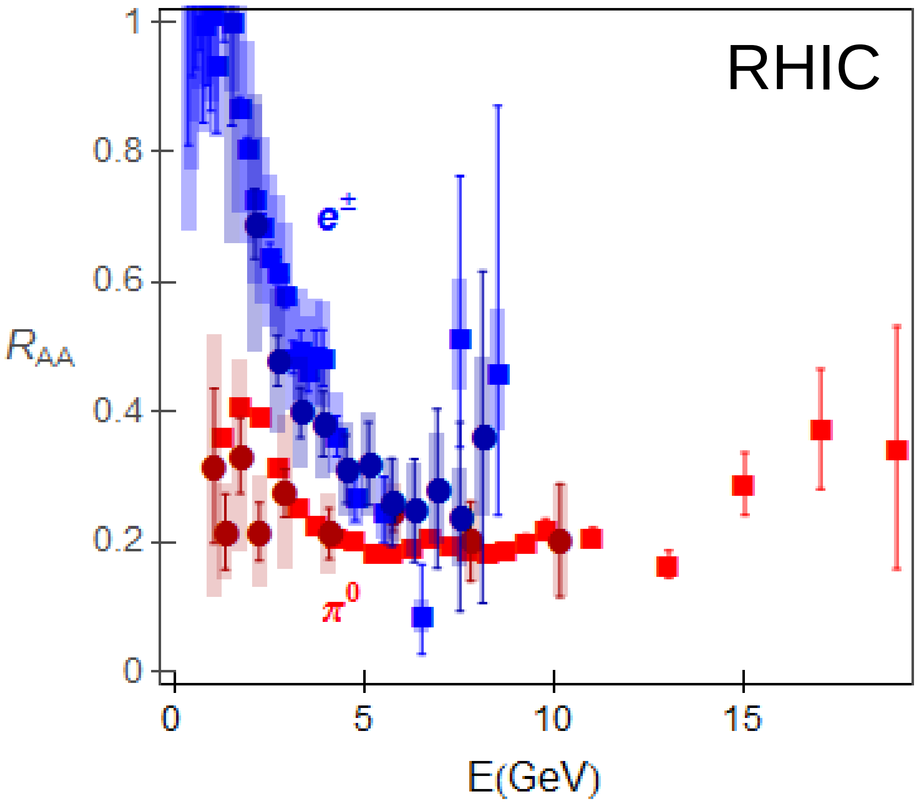
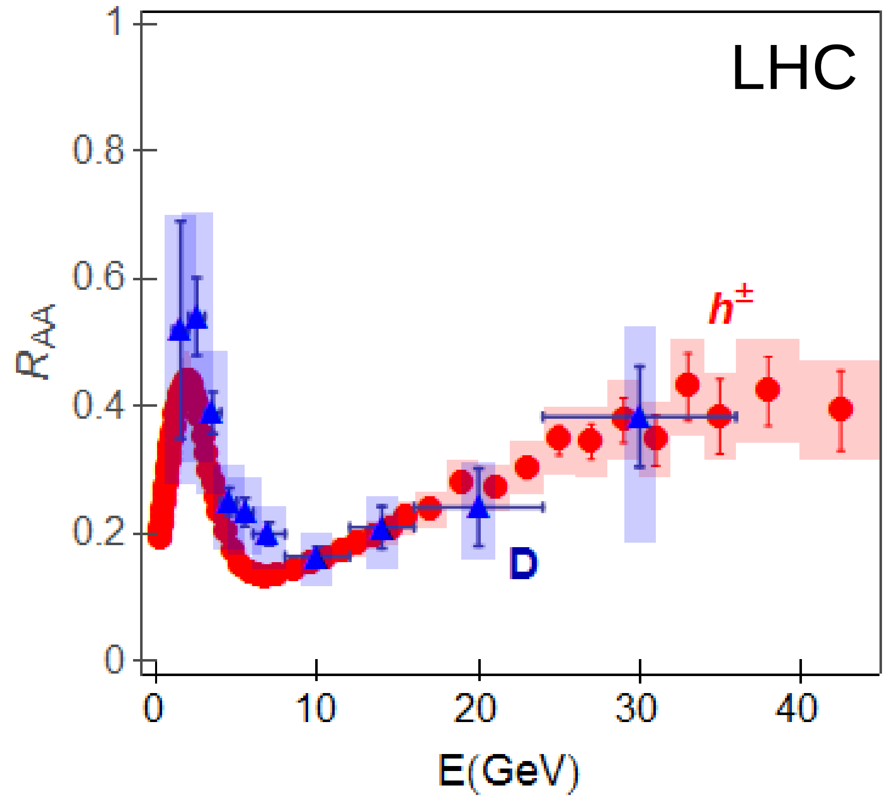
Addressing this puzzles from a pQCD perspective is the main topic of this talk.

Puzzling RHIC and LHC suppression data





$R_{AA}(\pi^0) \sim R_{AA}(e^{\pm})$

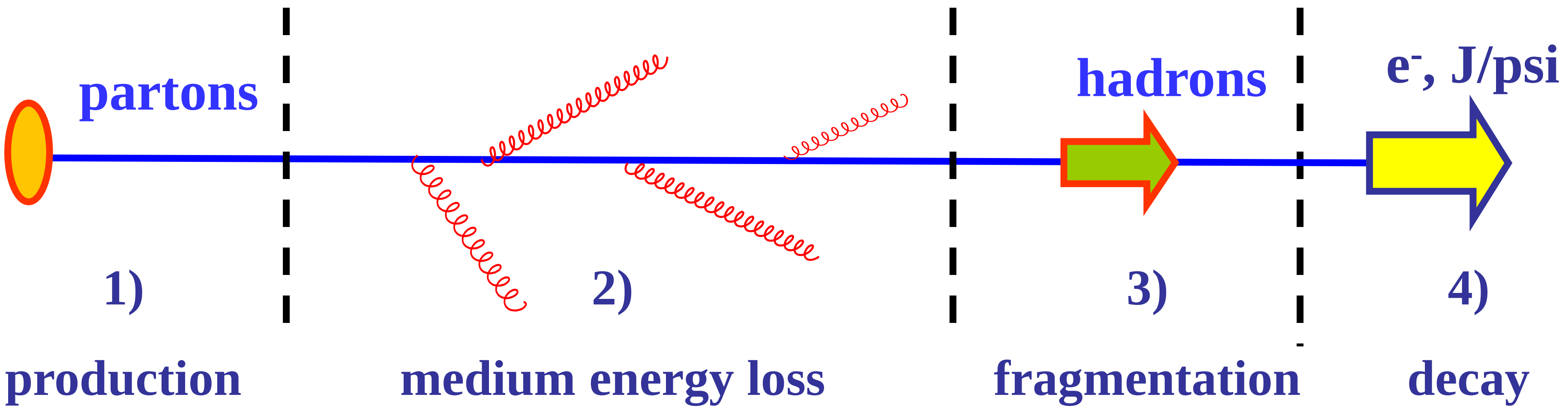
$R_{AA}(h^{\pm}) = R_{AA}(D)$

Unexpected results!

Overview

- **Concentrate on puzzling data – can pQCD explain them?**
- **Review of suppression pQCD calculations**
- **Some recent improvements – dynamical scattering centers, finite magnetic mass, running coupling**
- **Discussing LHC data**
- **Discussing RHIC data**
- **What we learned and what are immediate challenges?**

Jet suppression



1) Initial momentum distributions for partons
2) Parton energy loss
3) Fragmentation functions of partons into hadrons
4) Decay of heavy mesons to single e^- and J/psi.

Jet energy loss

Initially, most of the energy loss calculations assumed only *radiative* energy loss, and a QCD medium composed of static scattering centers. (e.g. GW, DGLV, ASW,BDMPS...)

However, these calculations lead to an obvious disagreement with the experimental data.

Is collisional energy loss also important?

Yes, collisional and radiative energy losses are comparable!

Non-zero collisional energy loss - a fundamental problem

Static QCD medium approximation (modeled by Yukawa potential).

With such approximation, collisional energy loss has to be exactly equal to zero!

However, collisional and radiative energy losses are shown to be comparable.

Introducing collisional energy loss is necessary, but inconsistent with static approximation!

Static medium approximation should not be used in radiative energy loss calculations!

Dynamical QCD medium effects have to be included!

Dynamical energy loss

We developed the radiative jet energy loss formalism in a finite size dynamical QCD medium.

Abolishes approximation of static scatterers.

We computed the jet radiative energy loss in dynamical medium of thermally distributed massless quarks and gluons.

$$\frac{\Delta E_{\mathrm{dyn}}}{E} = \frac{C_R \alpha_s}{\pi} \frac{L}{\lambda_{\mathrm{dyn}}} \int dx \frac{d^2k}{\pi} \frac{d^2q}{\pi} \frac{\mu^2}{q^2(q^2+\mu^2)} \left(1 - \frac{\sin \frac{(\mathbf{k}+\mathbf{q})^2+\chi}{xE^+} L}{\frac{(\mathbf{k}+\mathbf{q})^2+\chi}{xE^+} L}\right)$$
$$\times 2 \frac{(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi} \left(\frac{(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi} - \frac{\mathbf{k}}{\mathbf{k}^2+\chi}\right),$$

$$\chi \equiv M^2 x^2 + m_g^2$$

$$\lambda_{\mathrm{dyn}}^{-1} \equiv C_2(G) \alpha_s T = 3 \alpha_s T$$

M. D., Phys.Rev.C80:064909,2009.

M. D. and U. Heinz, Phys.Rev.Lett.101:022302,2008.

Finite magnetic mass

The dynamical energy loss formalism is based on HTL perturbative QCD, which requires zero magnetic mass.

↓

However, different non-perturbative approaches show a non-zero magnetic mass at RHIC and LHC.

↓

Can magnetic mass be consistently included in the dynamical energy loss calculations?

Generalization of radiative jet energy loss to finite magnetic mass

$$\frac{\Delta E_{\rm dyn}}{E} = \frac{C_R \alpha_s}{\pi} \frac{L}{\lambda_{\rm dyn}} \int dx \frac{d^2k}{\pi} \frac{d^2q}{\pi} \frac{\mu^2}{q^2(q^2+\mu^2)} \times 2 \frac{(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi} \left(\frac{(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi} - \frac{\mathbf{k}}{\mathbf{k}^2+\chi} \right) \left(1 - \frac{\sin \frac{(\mathbf{k}+\mathbf{q})^2+\chi}{xE^+} L}{\frac{(\mathbf{k}+\mathbf{q})^2+\chi}{xE^+} L} \right)$$

zero magnetic mass

From our analysis, only this part gets modified.

Finite magnetic mass: $\frac{\mu_E^2 - \mu_M^2}{(q^2+\mu_E^2)(q^2+\mu_M^2)}$**, where** $0.4 \le \frac{\mu_M}{\mu_E} \le 0.6$.

M.D. and M. Djordjevic, Phys.Lett.B709:229,2012

Dynamical energy loss - summary

Computed both collisional and radiative energy loss, in a finite size QCD medium, composed of dynamical scatterers.

M. D. PRC 80:064909 (2009), M. D. and U. Heinz, PRL 101:022302 (2008).

Finite magnetic mass effects.

M. D. and M. Djordjevic, PLB 709:229 (2012)

Includes running coupling

M. D. and M. Djordjevic, arXiv:1307.4098

Considers *finite size* optically *thin* QCD medium.

Complementary to AMY, which considers *infinite size* optically *thick* QCD medium.

Numerical procedure

- **Light flavor production** Z.B. Kang, I. Vitev, H. Xing, PLB 718:482 (2012)
- **Heavy flavor production** M. Cacciari et al., JHEP 1210, 137 (2012)
- **Path-length fluctuations** A. Dainese, EPJ C33:495,2004.
- **Multi-gluon fluctuations**

  M. Gyulassy, P. Levai, I. Vitev, PLB 538:282 (2002).
- **DSS and KKP fragmenation for light flavor**

  D. de Florian, R. Sassot, M. Stratmann, PRD 75:114010 (2007)

  B. A. Kniehl, G. Kramer, B. Potter, NPB 582:514 (2000)
- **BCFY and KLP fragmenation for heavy flavor**

  M. Cacciari, P. Nason, JHEP 0309: 006 (2003)
- **Decays of heavy mesons to single electron and J/psi according to**

  M. Cacciari et al., JHEP 1210, 137 (2012)
- **Temperature T=304 MeV for LHC and T=221 MeV for RHIC.**

  M. Wilde, Nucl. Phys. A 904-905, 573c (2013) (ALICE Collab.)

  A. Adare *et al.*, Phys. Rev. Lett. 104, 132301 (2010) (PHENIX Collab.)

Generating predictions

- **Provide joint predictions across diverse probes**

  charged hadrons, pions, kaons, D mesons,

  non-photonic single electorns, non-prompt J/ψ

  M. D. and M. Djordjevic, arXiv:1307.4098

- **Puzzles (apparently surprising data)**

  Measured charged hadron *vs.* D meson supression

  M. D., arXiv:arXiv:1307.4702

- **Fine resolution hierarchy**

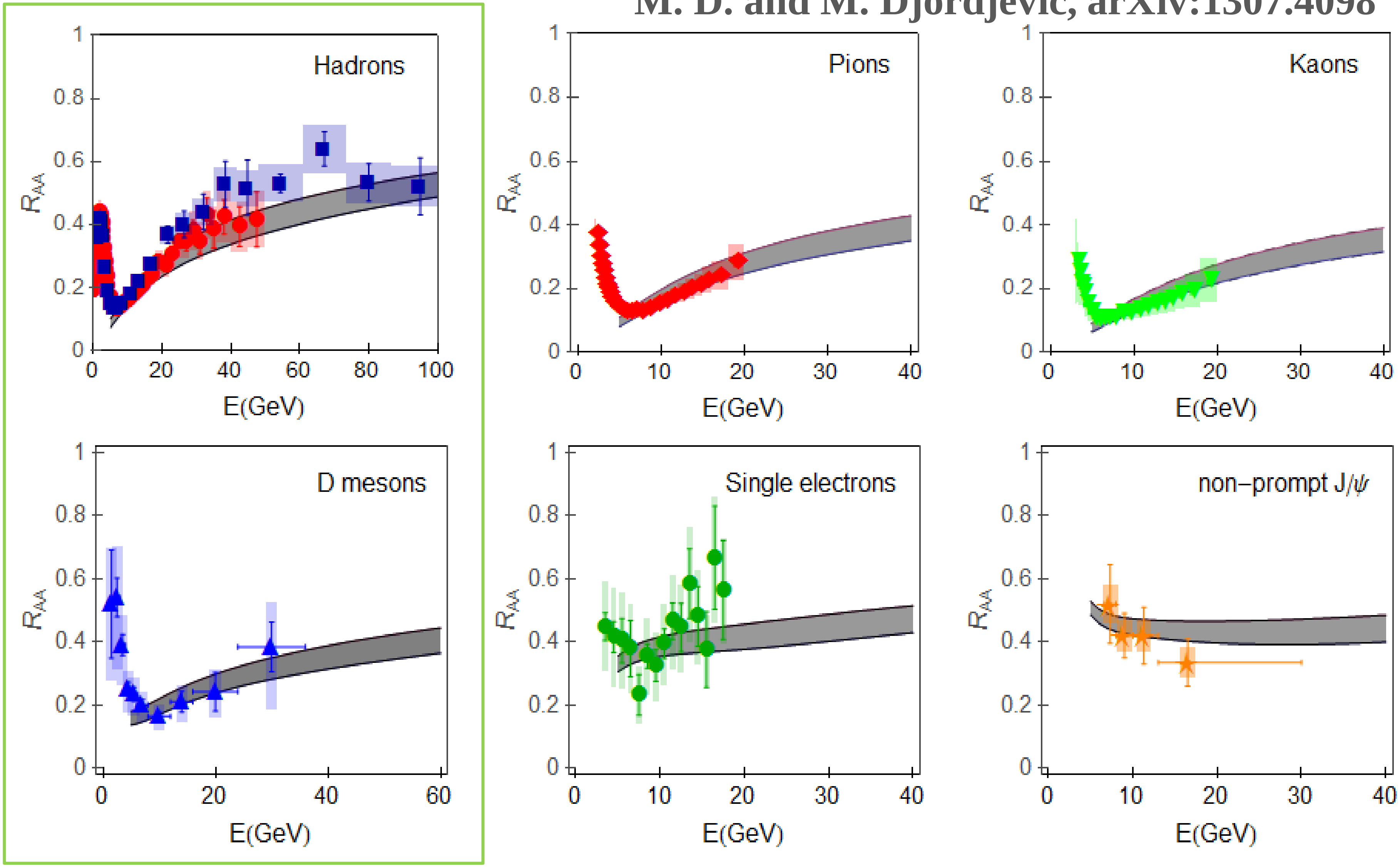
  Measured pion *vs.* kaon suppression

  M. D. and M. Djordjevic, arXiv:1307.4714

- **All predictions generated**
  - **By the same formalism**
  - **With the same numerical procedure**
  - **No free parameters in model testing**

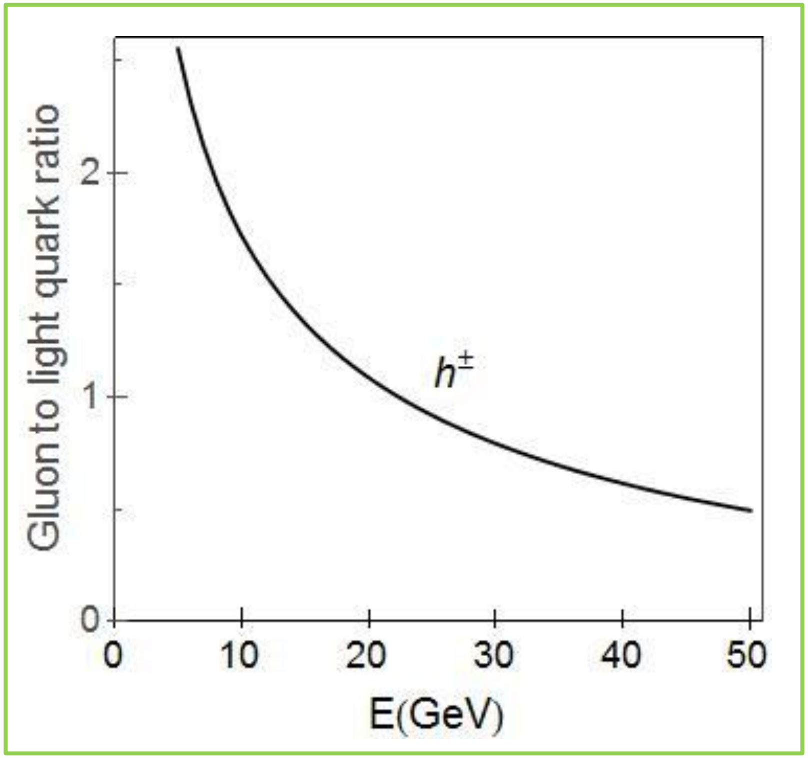
Comparison with LHC data

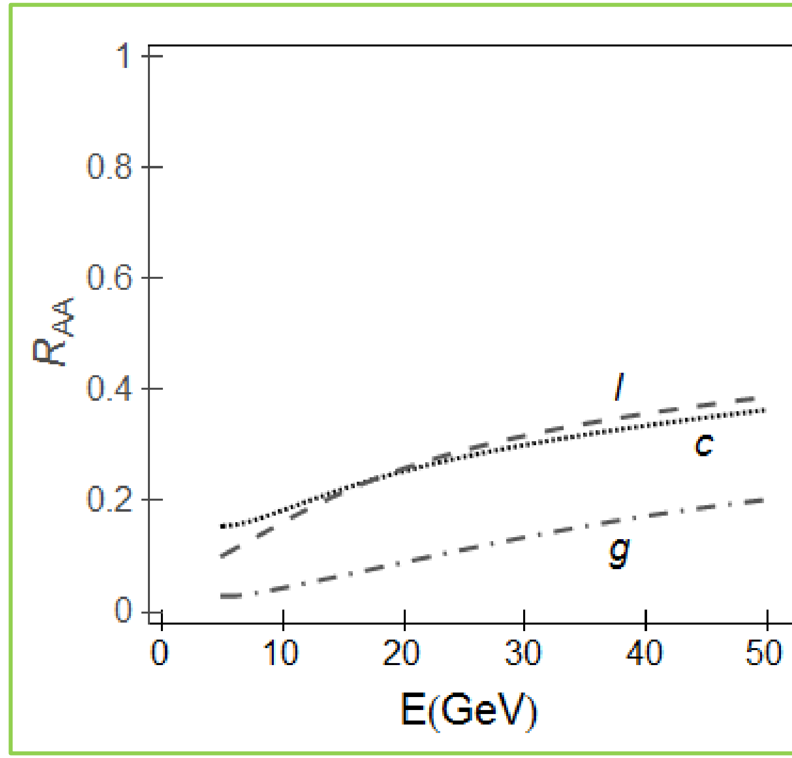
M. D. and M. Djordjevic, arXiv:1307.4098



Very good agreement with diverse probes!

Heavy flavor puzzle at LHC



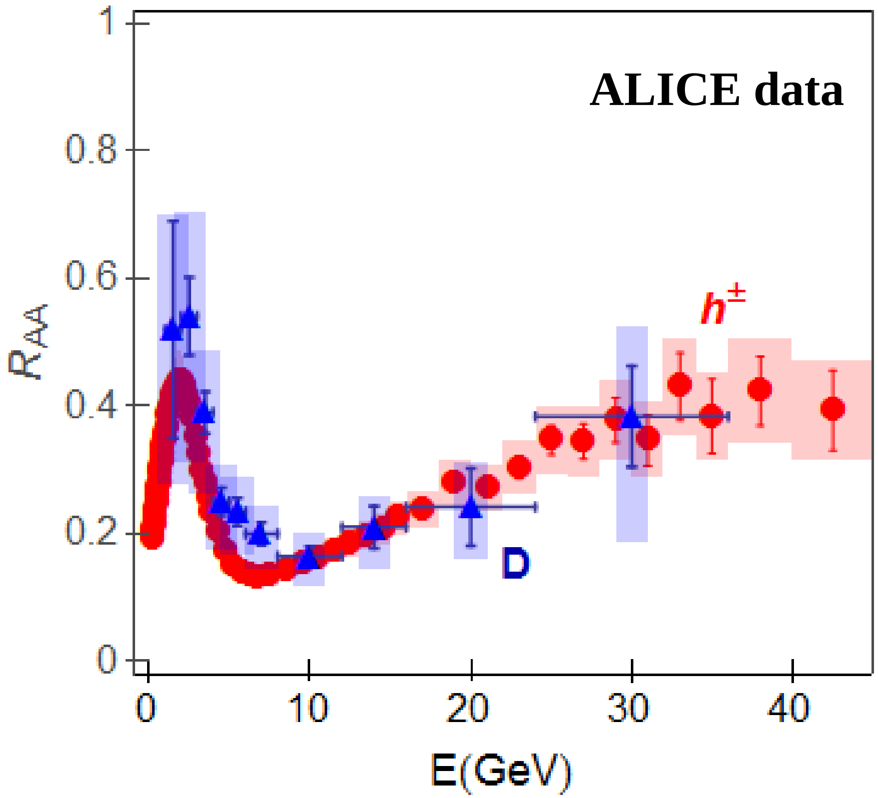


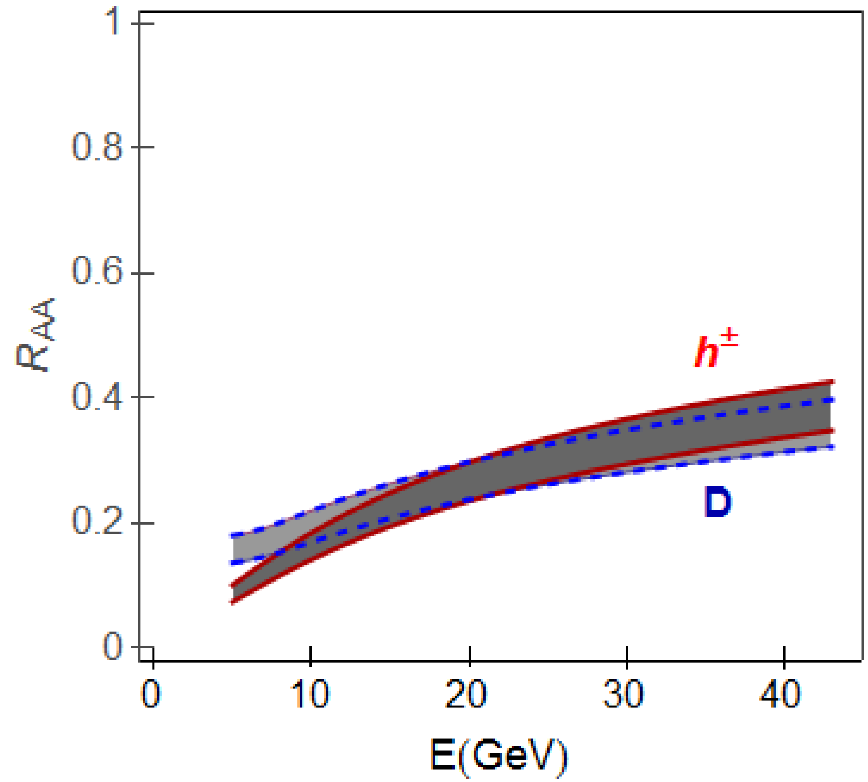
Significant gluon contribution in charged hadrons

Much larger gluon suppression

$$R_{AA}\,(h^{\pm}) < R_{AA}\,(D)$$

Charged hadrons vs D meson R_{AA}





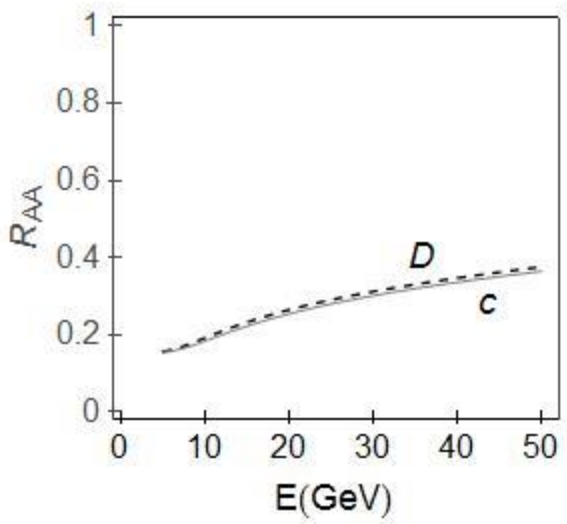
R_{AA} ($h^{\pm}$) = R_{AA} (D)

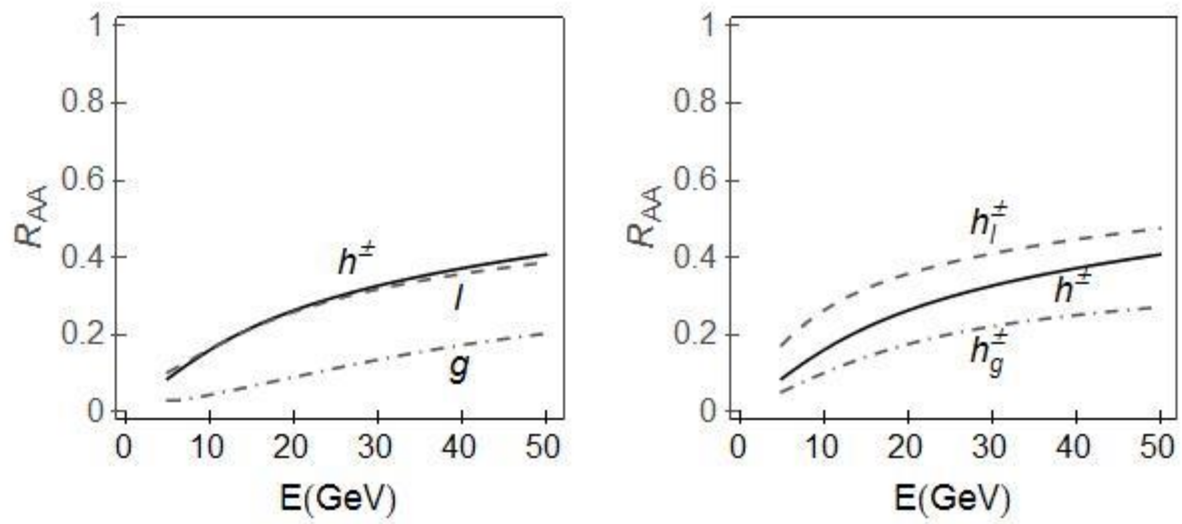
Excellent agreement with the data!

Disagreement with the qualitative expectations!

M. D., arXiv:arXiv:1307.4702

Hadron R_{AA} *vs.* parton R_{AA}





D meson is a genuine probe of bare charm quark suppression

Distortion by fragmentation

Charged hadron R_{AA} = light quark R_{AA}

M. D., arXiv:arXiv:1307.4702

Puzzle summary

R_{AA} ($h^{\pm}$) = R_{AA} (light quarks)

R_{AA} (D) = R_{AA} (charm)

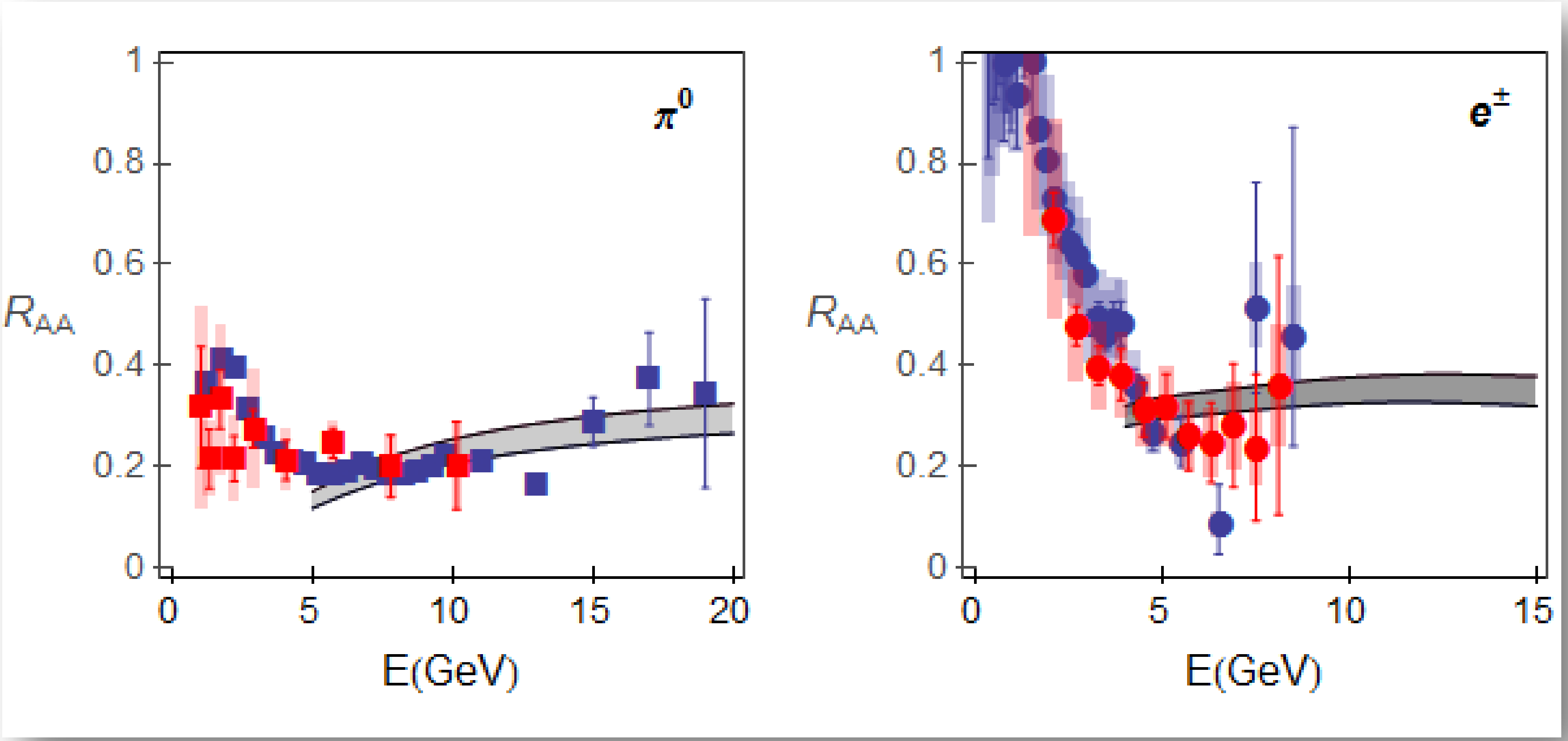
R_{AA} (light quarks) = R_{AA} (charm)

R_{AA} ($h^{\pm}$) = R_{AA} (D)

Puzzle explained!

M. D., arXiv:1307.4702

Comparison with RHIC data



Very good agreement!

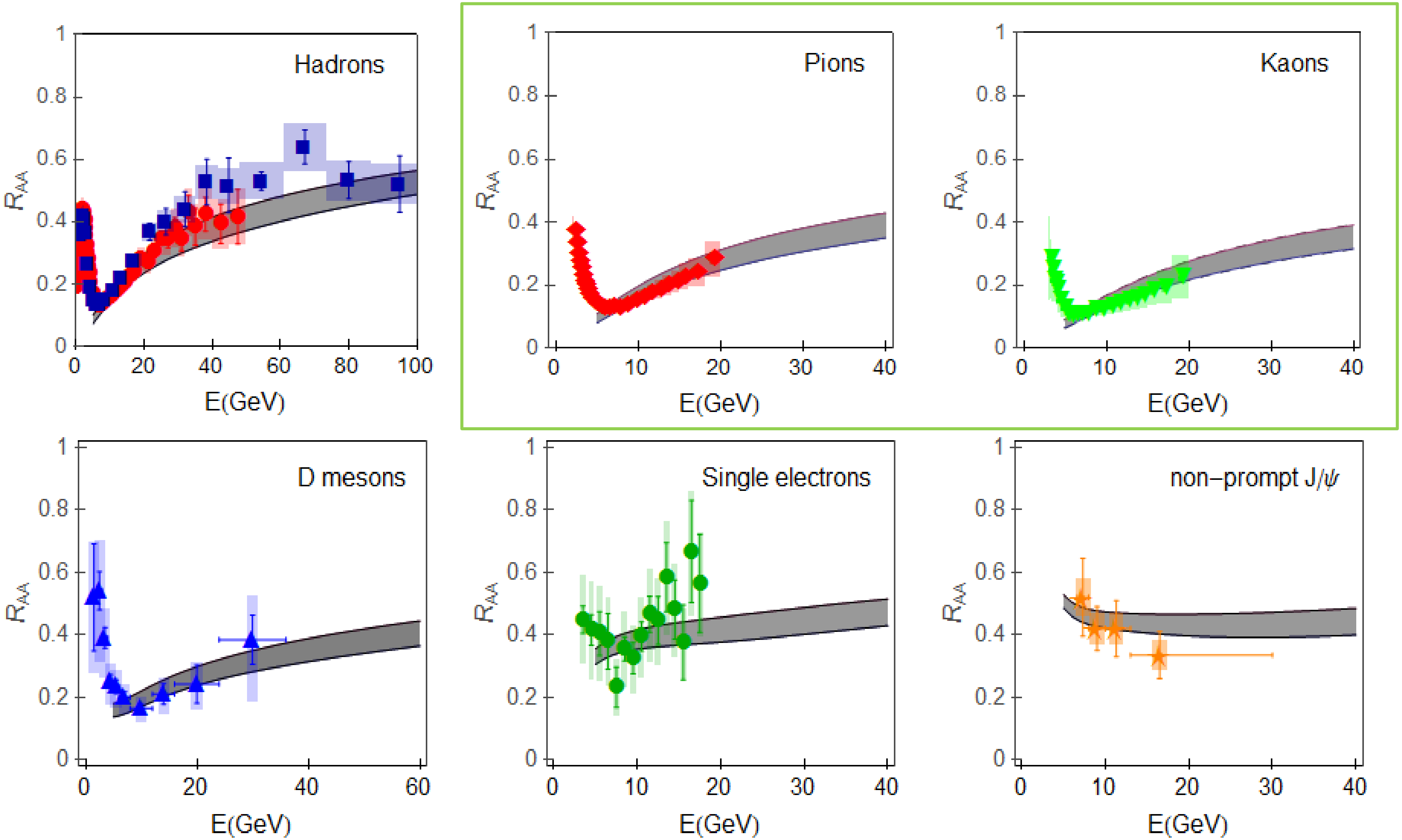
Importance of fragmentation functions

Traditionally, jet suppression studies mainly concentrate on energy loss.

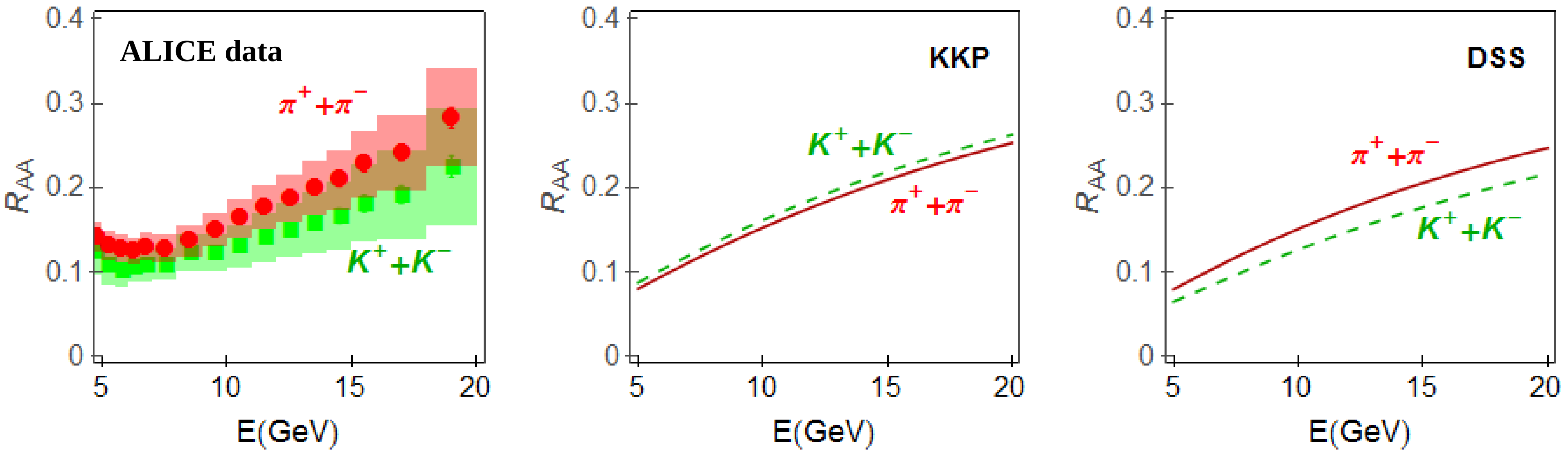
However, the puzzles at both RHIC and LHC show that fragmentation functions can be equally important.

Are there other examples where such interplay between fragmentation and energy loss can be observed?

Fine resolution hierarchy



Pion *vs.* kaon R_{AA}



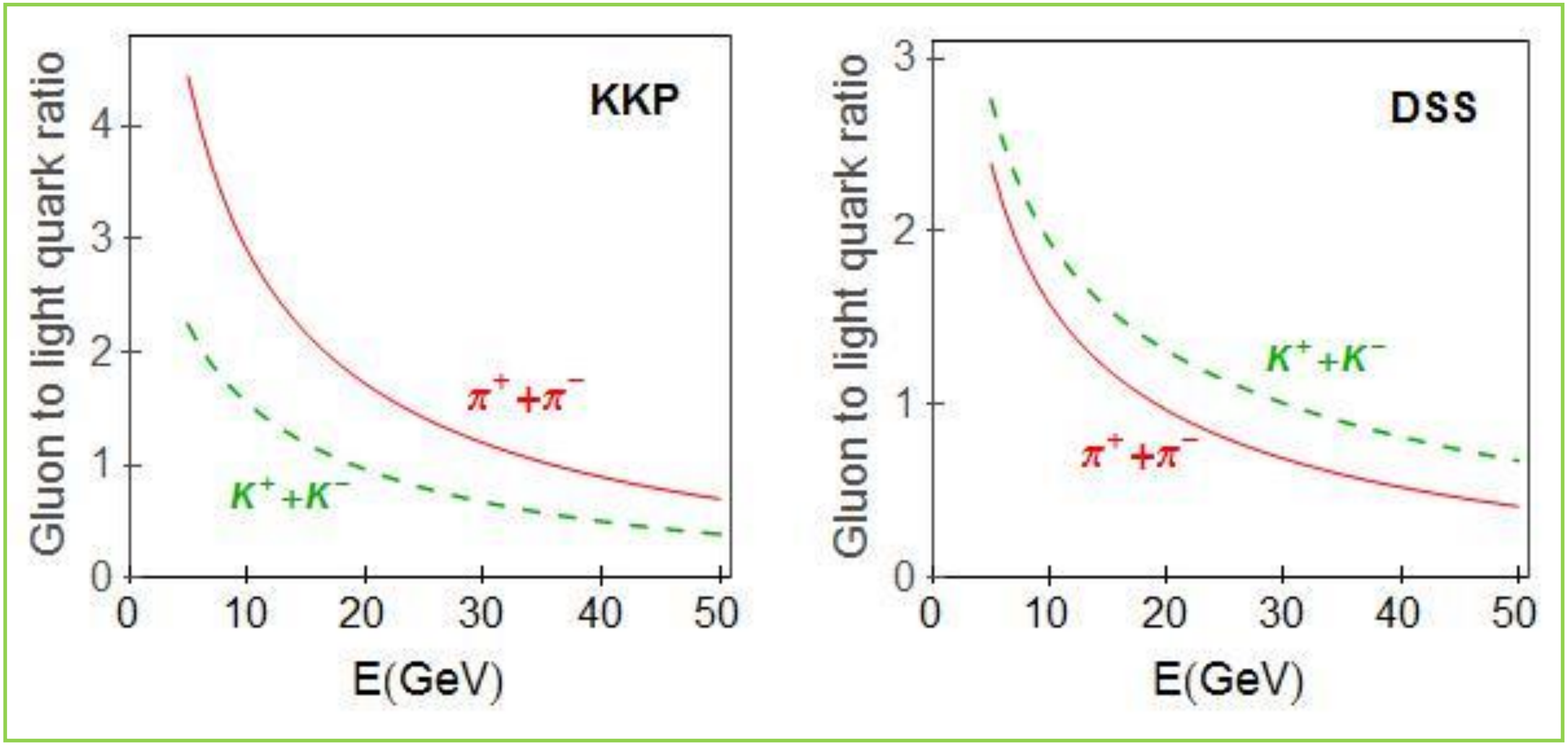
Clear (fine resolution) hierarchy between pion and kaon R_{AA}s.

Disagreement

Agreement

M. D. and M. Djordjevic, arXiv:1307.4714

KKP *vs.* DSS



A reversed hierarchy in gluon to light quark contributions!

M. D. and M. Djordjevic, arXiv:1307.4714

Summary

pQCD can simultaneously explain measurements for a diverse set of probes at both RHIC and LHC.

The formalism can explain puzzling data ("the heavy flavor puzzles at RHIC and LHC") and fine resolution data.

Charged hadron suppression is a genuine probe of light quark suppression.

Immediate challenge: extend the predictions to non-central collisions and elliptic flow.

Acknowledgement

Ministry of Science and Education in Serbia

FP7 Marie Curie International Reintegration grant

L'Oreal UNESCO For Women in Science Serbia

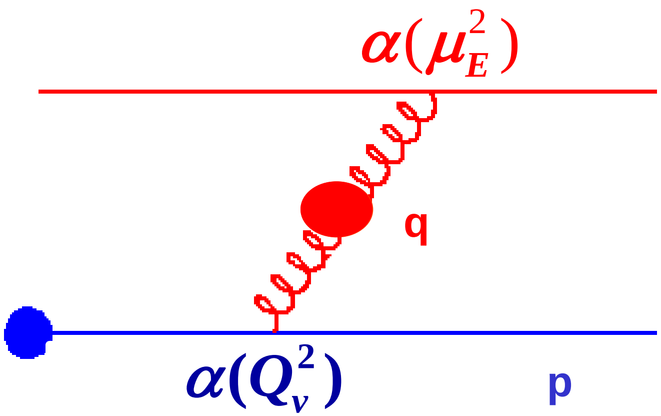
Many thanks to:

- **M. Djordjevic for collaboration on this project.**
- **I. Vitev and Z. Kang for providing the initial light flavor distributions and useful discussions.**
- **M. Cacciari for useful discussions on heavy flavor production and decay processes.**
- **ALICE Collaboration for providing the preliminary data**
- **M. Stratmann and Z. Kang for help with DSS fragmentation functions.**

Running coupling

Collisional energy loss

S. Peigne, A. Peshier, Phys. Rev. D **77**, 114017 (2008).



$$\Delta E_{coll} \sim \alpha(Q_v^2)\,\alpha(\mu_E^2)$$

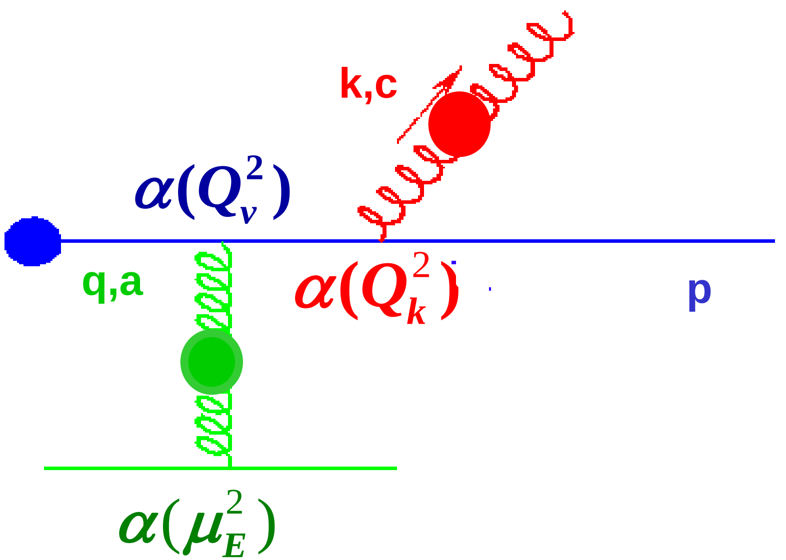
$$\alpha_S(Q^2) = \frac{4\pi}{(11 - 2/3 n_f)\ln(Q^2/\Lambda_{QCD}^2)}$$

$$\frac{\mu_E^2}{\Lambda_{QCD}^2}\ln\left(\frac{\mu_E^2}{\Lambda_{QCD}^2}\right) = \frac{1+n_f/6}{11-2/3\,n_f}\left(\frac{4\pi T}{\Lambda_{QCD}}\right)^2$$

A. Peshier, hep-ph/0601119 (2006)

Radiative energy loss

M. D. and M. Djordjevic, arXiv:1307.4098



$$\Delta E_{rad} \sim \alpha(Q_k^2)\,\alpha(Q_v^2)\,\alpha(\mu_E^2)$$

$$Q_v^2 = ET$$

$$Q_k^2 = \frac{\mathbf{k}^2 + M^2 x^2 + m_g^2}{x}$$